APPENDIX E

Contributions to the Nation

Developments in accelerator science and technology during the past 50 years have spawned a number of applications which have improved the quality of life for the general population. In most cases these improvements are taken for granted, and the average citizen is unaware of the connection between accelerators and the benefit he or she is receiving. This Appendix describes significant medical, industrial, military, and energy production applications which depend on accelerator technology.

E.1 Medical Applications

Many of the most advanced techniques in medical imaging and radiation therapy are direct spinoffs of accelerator development. Historically, there has always been a close relationship between physics and medicine, which has led to rapid transfer of technology from basic physics research to practical medical applications. The U.S. Department of Energy (DOE) can be particularly proud of the contributions it has made to medicine.

Radioactive Isotopes—DOE and its predecessor agencies have long supported the development and medical application of radioactive isotopes. This was an early and extremely successful example of technology transfer, which has allowed the creation of both the radiopharmaceutical and nuclear medicine instrumentation industries. In diagnostic nuclear medicine, radioactive chemicals at tracer levels are administered to patients and gamma rays emitted from the radioactive tracer are detected by a gamma camera, which uses computer techniques to reconstruct an image of the distribution of tracer in the body. Such imaging provides information about organ function and metabolism. At present one out of every three hospitalized patients in the United States undergoes a nuclear medicine procedure. In excess of 36,000 diagnostic medical procedures that utilize radioisotopes are performed daily in the United States, and a growing number of therapeutic procedures as well (approximately 200,000 annually). The total value of this use is estimated at $7-10B per year. In addition, there are close to 100 million laboratory tests annually that use radioisotopes to measure constituents of biological samples.

Approximately 20% of radiopharmaceuticals are based on accelerator produced isotopes. The most important and widely used of these is thallium (Tl)-201, which was originally developed at Brookhaven National Laboratory (BNL) in the 1970s. It is used to measure blood flow in heart muscle during exercise and is now produced commercially by proton irradiation of Tl-203 in a cyclotron at 28 MeV. Another important DOE development is the radiopharmaceutical F-18 deoxyglucose (FDG), which uses the accelerator-produced radioisotope fluorine-18. Originally developed at BNL in 1978, it is now the most widely used tracer for Positron-Electron Therapy (PET). FDG is a sugar analogue that can be used to study glucose metabolism in the brain, heart, and other organs. Many applications already exist in oncology (detection of tumor location and type, assessment of tumor response to surgical, drug or radiation therapy), neurology (early diagnosis of Alzheimer’s disease, location of seizure foci in epilepsy prior to surgical treatment, differential diagnosis of Parkinson’s disease, and brain function research), and cardiology (assessment of heart muscle viability). It is the only PET agent approved by the Food and Drug Administration for clinical rather than experimental use.

In addition, BNL and Los Alamos National Laboratory (LANL) have significant radioisotope production programs serving both the nuclear medicine research community and industry. The Brookhaven Linac Isotope Producer (BLIP) has used a 200-MeV, 45-microampere proton beam for this purpose since 1972, and is presently upgrading to 145 microamperes. The Los Alamos Meson Physics Facility (LAMPF) has delivered 800-MeV, 600-microampere protons for radioisotope production since 1975. Several unique, hard-to-make isotopes have been developed and are now distributed by these facilities. For example, strontium-82 is the parent in a generator system for creating the short-lived potassium analogue rubidium-82. This FDA-approved radioisotope system is used to assess cardiac function. The long-lived, positron-emitting germanium-68 is used to calibrate PET cameras throughout the world. Also, copper-67 is one of the most attractive radioisotopes for tumor therapy when attached to a tumor-specific monoclonal antibody.

Conventional Radiation Therapy—Over the past 25 years cobalt therapy machines for treating malignant tumors have been replaced by electron linear accelerators, which provide better and more flexible penetration of the therapy beams into the body. This allows the physician to raise the dose to the tumor while keeping the side effects comparable to those incurred during cobalt therapy. The linacs produce 4-25 MeV electron beams which strike a tungsten target to generate photons for treating cancer with radiation therapy. In some cases the electron beam is used to treat superficial tumors directly. The linac is typically one to two meters long and mounted on a gantry so it can rotate around a supine patient. A dipole magnet bends the beam perpendicular to the linac and the patient is positioned so the beam strikes the tumor. These linacs cost $1-2M and are used to provide radiation therapy at most large hospitals throughout the United States and other technologically advanced countries. About five major corporations dominate the competitive market, including Varian Associates and General Electric in the United States.

Proton Cancer Therapy—This promising therapy uses the proton Bragg peak to minimize unwanted dose to healthy tissue. For many types of cancer, it has the same probability of tumor control as photons, but with significantly fewer side effects. For harder-to-control tumors it allows the physician to prescribe a much higher tumor dose than would be possible with conventional photon radiation therapy. Pioneering work was done at Lawrence Berkeley National

Laboratory (LBNL) using the 184-Inch Synchrocyclotron, and the research has been continued at the Harvard Cyclotron. The first hospital-based synchrotron for proton therapy was built by Fermi National Accelerator Laboratory (Fermilab) and installed at Loma Linda University Medical Center in the late 1980s. Use of the first commercially manufactured radiofrequency quadrupole (RFQ) linac substantially reduced the size and cost of the Loma Linda accelerator. A 70- to 300-MeV variable-energy proton therapy synchrotron has been commercialized in United States by Elektus, and a 235-MeV cyclotron can be purchased from Ion Beam Applications in Belgium. A superconducting cyclotron for proton therapy is being developed at Michigan State University's National Superconducting Cyclotron Laboratory (NSCL).

Fast Neutron Cancer Therapy—This is the first form of hadron therapy to be investigated. Early initiatives at Berkeley revealed the importance of the concept of Relative Biological Effectiveness in understanding neutron dosimetry. The high reliability and favorable dose rate of the 66-MeV proton beam from Fermilab's injector linac enabled Fermilab to set the standard for the beam qualities required for effective fast neutron therapy. This therapy is superior to photon therapy for some radioresistant tumors, including salivary tumors, soft tissue and bone sarcomas, adenocarcinoma of the lung, and advanced prostate cancer. AccSys Technology has developed a hospital-based linac for neutron therapy, and the NSCL has developed a hospital-based superconducting cyclotron.

Heavy-Ion Cancer Therapy—Heavy ion therapy combines the advantages of the Bragg peak seen in proton therapy with the biological effectiveness seen in fast neutron therapy. This combination makes heavy ion therapy a very attractive option for many types of tumor. Pioneering work was done at LBNL's Bevalac. Unfortunately, all clinical research with this therapy in the United States was terminated with the closing of the Bevalac, though the therapy is available in Japan. Several European countries have plans to build heavy-ion therapy centers.

Pion Cancer Therapy—Pioneering work with pi mesons was done at Stanford using their high-energy electron linac and at LANL using the LAMPF linac. The most extensive clinical research with this therapy was done at Paul Scherrer Institute (PSI) in Switzerland using technology developed in the United States. The PSI clinical results were similar to those for fast neutrons, though the cost of producing pions is much greater. PSI terminated its pion research in favor of proton therapy research, but pion therapy is available at the TRIUMF accelerator in Canada.

Coronary Angiography—By using radiation from a synchrotron rather than conventional X-ray machines it is possible to inject the iodine contrast agent into a vein rather than an artery to obtain an image of the heart. Injection into a vein makes the procedure much safer for the patient and enables clinicians to image the hearts of patients who might not be candidates for the more dangerous conventional procedure. Use of synchrotron light for coronary angiography was pioneered at the Stanford Synchrotron Radiation Laboratory, and the technology was transferred to the National Synchrotron Light Source at BNL, where physicians and physicists are performing clinical trials and fine-tuning the technique. Coronary angiography using conventional X-rays is a $2B per year industry.

Designer Drugs—High-resolution X-ray crystallography using synchrotron radiation has enabled researchers to understand the detailed structures of proteins, enzymes, and viruses. Using this knowledge, they are designing drugs which alter these structures to fight disease more effectively.

E.2. Industrial Applications

Besides the economic benefit derived from knowledge acquired in the many research uses of accelerators, there are applications that add direct value to industrial goods and services. A selected list of such applications is shown below. It is not a complete list but rather a sampling across a broad range of application categories that are now commercially successful or are close to being brought to market.

Ion Implantation for Semiconductor Devices—One of the most widespread and economically important applications of particle accelerators is for ion implantation, in which beams of doping or alloy materials are implanted into metals or semiconductors to selectively alter material properties. Major applications of ion implantation are in the manufacturing of semiconductors and in the improvement of surface hardness and corrosion resistance of metallic devices.

Thousands of ion-implanting systems have been used by the semiconductor industry to produce embedded layers in silicon wafers doped as needed for various semiconductor devices. In processes that are now totally automated, the doping material species, depth of implant, and doping concentration can be carefully controlled to meet the exacting requirements for mass-produced, high quality devices. For example, the uniformity of doping concentration can be controlled to better than 1% across the wafer.

The economic impact of the ion implantation is large. As direct measure of value, we note that several companies now manufacture the implanting systems, which cost about $5M each. The multi-billion dollar per year semiconductor industry would be much different without the essential technology that makes many of their devices possible.

Ion Implantation for Surface Hardening—Surface hardening by ion implantation uses ion beams to alloy a thin surface layer with foreign atoms at concentrations hundreds of times the typical level used for semiconductor doping. This method is superior to the traditional thermal treatment and results in greatly enhanced surface hardness and resistance to wear and corrosion. Some examples include the surface treatment of prosthetic devices such as hip and knee joints to reduce wear of the moving parts while using biologically inert materials, surface hardening of high speed bearing surfaces, and the hardening of metal forming and cutting tools. Several DOE laboratories are currently involved in the continued development of these technologies.

Sterilization By Accelerator-Generated Radiation—Electron beams from a variety of low energy accelerators such as the Cockcroft-Walton, Dynamitrons or RF linacs are widely used for sterilization and other forms of industrial irradiation. As electrons penetrate materials they create radiation fields from showers of low energy electrons and photons. After many collisions the electrons have the proper energy to create chemically active sites. In sterilization, the radiation breaks down biological molecules to render them useless and, thus, kills the organism. Important applications include the sterilization of syringes, gloves, cosmetics, pharmaceuticals, and food. Accelerator beams have been used to sterilize sewage sludge so that it can be used safely as fertilizer. The compact electron linacs are a spinoff from linacs developed originally at Stanford Linear Accelerator Center (SLAC) and LAMPF for basic research.

Materials Irradiation—Radiation generated by electron beams can also be exploited to change material properties such as cross-linking a polymer to strengthen it, curing epoxies, production of shrink film and tubes, or radiolysis of toxic wastes to less toxic products. Other important applications include the removal of pollutants from utility stack gas and electron treatments to cure thin films and coatings. For applications requiring the lower energies, 1-5 MeV, conventional high-voltage generators can be used. Above about 5 MeV, the size and cost of these generators makes them impractical, and compact linacs are the technology of choice.

X-Ray Lithography—Lithography refers to the technique of shadow or proximity printing to replicate fine patterns on various materials. The pattern on a mask is transferred to a photoresist coating on a wafer using optical radiation or low energy X-rays. This process is most extensively used in the manufacture of microchips and other semiconductor devices. In a deep-etch process it is also used to produce micromachines. The interest in X-ray lithography stems from the finer spatial resolution possible with the shorter wave-length X-rays. Higher resolution means more microelectronic circuits per unit area on a chip, a very important factor in the highly competitive semiconductor industry, which thrives on a fast pace of technological improvements that yield ever increasing capability per unit cost.

Pioneering development work in X-ray lithography was done at the DOE and the National Science Foundation (NSF) synchrotron light sources. Currently, multi-GeV electron synchrotrons and storage rings are still the best sources of intense X-ray beams for lithography R&D. Ultimately, commercial use of X-ray lithography will require compact X-ray sources appropriate for industrial settings.

Explosives and Contraband Detection—Effective, non-destructive, automated methods of explosives and contraband detection would be of great benefit to the traveling public and ease the burden on inspection agencies. Systems based on such methods would reduce the inconvenience to travelers and enhance the security of airports and other transportation hubs. The feasibility of two accelerator-based concepts has been established. In one concept, accelerator-produced gamma rays and gamma-ray resonance absorption analysis are used to detect explosives. In the other, an accelerator-based inspection system employs pulsed fast neutron analysis (PFNA) for detection of drugs or explosives. At this time, further development is needed to achieve cost-effective, reliable systems that are likely to be commercially successful. Among DOE laboratories, LANL has been active in the development of accelerators for the gamma-ray resonance absorption technique. In industry, Science Applications International Corporation has developed, built, and is now testing a system using the PFNA concept.

Neutron Radiography Using Accelerator Sources—Neutron radiography is a well-established, nondestructive inspection technique used at reactor neutron sources. Major applications include inspection and checking of components such as turbine blades, reactor fuel components, small explosive devices, corrosion in aerospace parts, and hydrogen embrittlement in welds. Accelerator-produced neutron beams could meet the neutron beam requirements for commercial neutron radiography. Suitable beams could be produced by moderating and collimating neutrons produced by a few-MeV proton or deuteron beam striking a lithium or beryllium target. Transportability by truck is one advantage that an accelerator-based neutron radiography facility could have over a reactor-based facility. This opens up the possibility of inspecting objects too large or not transportable to a reactor hall. The RFQ accelerator technology could provide the proton or deuteron beams to meet the needs for low energy neutron radiography. (The RFQ was first developed at LANL for the DOE fusion energy program.) Neutron radiography also shows promise for the nondestructive inspection of nuclear weapon assemblies. This application requires a beam of several-hundred-MeV protons to produce neutrons using a spallation reaction.

E.3. Defense Applications

The U.S. continues to rely on its shrinking stockpile of nuclear weapons to deter strategic military threats to its national security. The strength of the deterrence is strongly tied to the reliability, safety and credibility of the aging stockpile. Accelerators contribute in increasingly important ways to the maintenance of the stockpile. They currently provide important radiographic diagnostics in hydrodynamic, non-nuclear simulation/testing of weapon primaries. Pulsed-power accelerators are used in the simulation of weapons effects for testing defense systems survivability.

Tritium is a key weapons ingredient that has a limited lifetime and must be replenished over time. Accelerator-based production of tritium (APT) is judged feasible and has the potential to supply tritium with fewer safety and environmental problems than a new production reactor. Accelerator-based neutron and proton radiography also show promise as important tools for stockpile stewardship.

Other issues in the management of the nuclear weapons complex that accelerators can address include accelerator-based conversion (ABC) of excess weapons plutonium to non-fissile material and accelerator transmutation of radioactive or fissile defense wastes (ATW) to short-lived isotopes or non-fissile materials. Finally, it should be noted that an accelerator-based, antiballistic missile system is another potential defense application that has been intensively developed but is still in its infancy.

Pulsed Radiography in Hydrodynamic Testing—Hydrodynamic testing refers to the above-ground, non-nuclear experimental study of the implosion process in the primary initiator system in a nuclear weapon. Without underground testing, it is the program that comes closest to experimental verification of device performance. Data from hydrodynamic testing is used to validate computer codes, study the effects of component aging, study sensitivity to environmental parameters, and assess weapons safety issues.

Accelerator-generated, very intense, short bursts of high-energy X-rays are used to radiograph the implosion. It is the one method capable of providing data from late in the implosion. The oldest pulsed radiographic linac in the weapons complex, PHERMEX at LANL, which dates from the 1960s, uses rf linac technology. To obtain much higher beam current, Lawrence Livermore National Laboratory (LLNL) built a radiographic induction linac, the FXR, and LANL is now constructing a dual-axis induction accelerator, DAHRT, for pulsed radiography. These induction linacs are capable of kiloampere electron beams at 15-20 MeV.

Weapons Effects Simulations—Pulsed power accelerators are a vital component in pulsed X-ray sources used to simulate the effects of nuclear explosions. For many years, above-ground simulators have supplemented underground testing of survivability and hardening of nuclear weapons and other defense systems. In the complete test ban environment, such non-nuclear studies assume much greater importance to maintaining the credibility of the U.S. nuclear deterrence. Sandia National Laboratories and various Department of Defense (DOD) labs have led in the development of nuclear weapons effects simulators.

Accelerator Production of Tritium—Replenishing the decaying tritium component of nuclear weapons is essential to maintaining any size stockpile. There is little doubt that accelerator production of tritium can meet the needs of the reduced stockpile planned for the future. The system design behind the proposed APT facility is based on well-established, existing technology in the areas of operational linear accelerators, tritium extraction and neutron production targets. The proposed APT facility has several advantages over reactor production of tritium in that APT uses no fissile materials, has no chance of a criticality accident, produces no high-level radioactive waste, and can easily be scaled up or down to meet stockpile needs. In addition, the LANL concept for APT has continual extraction of tritium that avoids buildup and thereby avoids the risk of a large release. Capital costs of APT are estimated to be less than for a new production reactor. APT is a spinoff from the high-power proton linac technology developed at LANL and other DOE laboratories.

Accelerator Transmutation of Waste and Conversion of Plutonium— Accelerator-driven transmutation of radioactive or fissile waste (ATW) is a concept that uses a high-intensity beam of protons up to 1.6 GeV to generate a very intense, high flux spallation neutron source. The spallation neutrons are thermalized in a moderating blanket and produce the flux needed to transmute long-lived actinide isotopes and fission products to stable isotopes or much-shorter-lived isotopes that decay to stable products. This ameliorates the very difficult technical and political problems of storing long-lived, high-level radioactive waste from nuclear weapons production and nuclear power plants.

Accelerator-based conversion of plutonium is a special form of ATW designed to convert weapons plutonium to a form that cannot be subverted for use in other nuclear weapons. It is aimed at converting excess plutonium from nuclear weapons dismantled as a result of stockpile reduction agreements. The immediate concern is to gain control of the material and prevent clandestine use in nuclear weapons.

The accelerator requirements for ATW are similar to those of APT, but the spallation neutron target requirements are more demanding. Both ATW and ABC are spinoffs from the high-power proton linac technology developed at LANL and other DOE laboratories.

Beam Weapons—Another potential application is accelerator-based anti-ballistic missile defense systems. They were studied and some received considerable development under the DOD Strategic Defense Initiative. The neutral particle beam project (NPB) and the free-electron laser projects were accelerator based and depended heavily on high-power rf linacs. The NPB project studied the use of neutral particle beams to perform several functions, including detecting the incoming missile, distinguishing it from decoys, and finally destroying the warhead before it could do harm. Many of the accelerator physics issues were resolved before the project was closed, but many engineering, operational, and cost issues remain. These applications were potential spinoffs from proton linac and free electron laser accelerator technology developed at DOE laboratories.

E.4. Energy Production

When deuterium and tritium atoms fuse, they release energy, which can be used for electrical power. It is important that the energy used to initiate the fusion reaction be less than the energy released in the reaction. Fusion has great long-term potential but is not yet commercially practical. Fission, on the other hand, has been proven practical, but concerns about safety and radioactive waste have limited construction of reactors. In this section, we describe two promising accelerator-based methods for energy production. These are heavy-ion fusion (HIF), a form of inertial fusion, and accelerator-based fission reactors. Research on the high-intensity accelerators required for both concepts is being pursued in the DOE.

Heavy Ion Fusion—This method of fusion uses intense beams of heavy ions to compress and ignite a small pellet of inertially confined deuterium-tritium fuel. The late Alfred Maschke first proposed using heavy ions in 1975, based on his experience with high-energy accelerators at Fermilab and BNL. Maschke recognized the advantages of heavy ions, since confirmed by a number of national reviews, including a National Academy review. The current DOE program is centered at Berkeley with additional effort at LLNL. The research involves a series of experiments to validate methods for increasing the beam intensity while keeping costs down.

The HIF effort is coordinated with the inertial fusion research program in DOE's Defense Programs, which is based on lasers and light ion beams. Also, good interaction exists between the U.S. effort and European research, concentrated in Germany. The European effort is based on rf accelerators while the U.S. effort emphasizes induction linacs.

Accelerator-Based Fission—Use of an accelerator-based neutron source to initiate fission in a sub-critical reactor is inherently safer than the methods currently used in fission power plants. Use of a sub-critical assembly eliminates the possibility of a runaway chain reaction; if the linac is off, the fission reaction shuts down quickly. Other safety features include reduced after-heat, less production of high-level radioactive waste and the possibility of burning or transmuting its own radioactive waste. The rf linac needed for accelerator-based fission is similar to that required for accelerator-based tritium production (APT) for DOE's Defense Programs. LANL scientists and others have studied methods for achieving the required higher intensity, and currently LANL has a program to begin development of such a linac.

Many of the developments in both of the above programs regarding high intensity have spinoff potential to other DOE accelerator programs and illustrate the synergism of such programs.